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P. van der Merwe

J. S. Coetsee

G. J. van den Berg

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THE EFFECT OF WORKHARDENING AND RESIDUAL STRESSES DUE TO COLD WORK OF FORMING ON THE STRENGTH OF COLD–FORMED STAINLESS STEEL LIPPED CHANNEL SECTIONS

Coetsee, J.S.[1], Van den Berg, G.J.[2], Van der Merwe, P.[3]

ABSTRACT

The purpose of this investigation was to obtain the necessary information on the effects of workhardening and residual stresses due to cold work of forming on the strength of cold–formed stainless steel lipped channel sections. A comparison was made between the mechanical properties of the virgin sheet, the weighted average mechanical properties of a section determined by cutting the section into flat and corner strips and the mechanical properties of a section determined through stub column tests. It can be concluded that the difference in strength between the weighted average stress–strain curve and the stub column stress–strain curve is due to residual stresses in the section caused by cold forming.

GENERAL REMARKS

Changes in the mechanical properties of steel sheets and plates are brought about by workhardening induced by cold forming, such as brake forming and deep drawing. These changes can be an increase in yield strength and ultimate strength and decrease in ductility. Such changes in the mechanical properties depend on the chemical composition of the steel, its prior metallurgical history, its prior history of cold work and the type and magnitude of plastic strains caused by the cold work.[1] The mechanical properties of cold–formed sections are thus sometimes substantially different from that of virgin sheet before forming. The mechanical properties in various parts of the cross section are different because the material in the corners is cold–worked to a considerably higher degree than the material in the flat elements.

When a steel member is formed into its final form there are stresses left in the member and these stresses are called residual stresses. The residual stresses in cold–formed members are caused by the cold forming process while the residual stresses in hot—rolled and welded shapes are caused by the uneven cooling after hot rolling or welding.

Galambos[2] derived a general equation for the stress–strain relationships of hot–rolled carbon steel wide flange cross sections. He concluded that if the residual stresses are neglected it will cause earlier yielding than is expected and a reduction in stiffness of the member. Figure 1 shows typical stress–strain curves for residual free test coupons and members with residual stresses. Yu[3] reported that although the effect of residual

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1. Research Assistant in the Materials Laboratory in the Faculty of Engineering at the Rand Afrikaans University. Republic of South Africa

2. Associate Professor, Chairman of Civil Engineering and Chairman of the Materials Laboratory in the Faculty of Engineering at the Rand Afrikaans University. Republic of South Africa.

3. Professor of Mechanical Engineering and Dean of the Faculty of Engineering at the Rand Afrikaans University. Republic of South Africa.

stresses may not be very great as far as the ultimate stress is concerned, the residual stresses will nevertheless lower the proportional limit. Also the inelastic behaviour of members can not be predicted correctly without consideration of the residual stresses.

As shown in Figure 1 the shape of the stress–strain curve for carbon steels is influenced by the residual stresses in that the proportional limit is significantly reduced. The stress–strain curve of the member changed to a gradual yielding curve. Stainless steels yield gradually under load. It will be shown in this study that the influence of residual stresses on the strength of cold–formed stainless steel structural members differ to that of cold–formed carbon steel members.

MATERIALS UNDER CONSIDERATION

The stainless steels under consideration in this study are limited to annealed AISI types 304 and 316 as well as a modified Type 409 stainless steel designated 3CR12, a corrosion resisting steel manufactured by the specially steel producing company, Middelburg Steel and Alloys.

STAINLESS STEEL TYPE 304

Stainless steel, Type 304 is an austenitic stainless steel and is commonly available. It has a wide range of applications such as architectural, brewing industry, cook ware, cryogenic plants, food and dairy processing equipment, heat exchanger tubes and supports, pressure vessels and process plants. It has a corrosion resistance in industrial areas where there is a combination of moisture, carbonaceous and other pollutants.

STAINLESS STEEL TYPE 316

Stainless steel Type 316 is an austenitic stainless steel and have almost the same characteristics as Type 304 stainless steel except that it is more corrosion resistant and is thus more expensive.

TYPE 3CR12 CORROSION RESISTING STEEL

Type 3CR12 corrosion resisting steel was developed by the specialty steel producing company, Middelburg Steel and Alloys from AISI Type 409 stainless steel. The aim with the development of this steel was to create a low chromium steel of which the mechanical properties and the weldability would be superior to that of Type 409. The chemical composition of this steel falls typically within the limits of Type 409, except for nickel, manganese and titanium. The carbon and nitrogen levels are kept low and it has therefore improved toughness over AISI Type 409 and 430 in both the annealed and welded conditions.

ANALYTICAL EQUATION FOR MECHANICAL PROPERTIES

The analytical stress–strain curves can be drawn by using the Ramberg–Osgood[4] equation as revised by Hill,[5] Johnson [6] and Wang.[7]

$$\epsilon = \frac{F}{E_0} + 0{,}002\left(\frac{F}{F_y}\right)^n \qquad (1)$$

where

$$\epsilon = \frac{\log\left(\frac{\epsilon_y}{\epsilon_p}\right)}{\log \frac{F_y}{F_p}} \qquad (2)$$

ϵ = strain
ϵ_y = yield strength offset strain
ϵ_p = proportional limit offset strain
F = stress
E_o = initial elastic modulus
F_y = yield strength
F_p = proportional limit
n = constant

It has been found in a study by Van der Merwe[8] en Van den Berg[9] that Equations 1 and 2 give conservative curves in the vicinity of the proportional limit, F_p. This equation will be used to compare the virgin sheet, weighted average and stub column stress–strain curves.

MECHANICAL PROPERTIES FOR VIRGIN SHEET

TESTING PROCEDURES

Uniaxial tensile and compression tests were carried out on specimens taken form the sheet in the longitudinal and transverse directions of rolling. The tensile and compression tests were conducted generally in accordance with the procedures outlined by the ASTM Standard, A370–77.[10] Average strain was measured by two strain gauges mounted on either side of the specimen in a full bridge configuration with temperature compensation. Compression test specimens were mounted in a specially manufactured compression test fixture which prevents buckling of the specimen about the minor axis. All specimens were tested using an Instron universal testing machine. A detailed testing procedure is given in Reference 9.

RESULTS

Stainless steels yield gradually under load. This is in contrast to carbon and low alloy steels. In order to compute the initial elastic modulus, E_o, and subsequently the proportional limit, F_p, defined as the 0,01% offset strength, and the yield strength, F_y, defined as the 0,2% offset strength, a computer program has been developed. This program enables the computation of the best fit straight line for the initial part of the stress–strain curve through a process of iterative linear regression. The slope of the best fit straight line is considered to be the initial elastic modulus, E_o. The experimental data is then shifted along the strain axis to accommodate the initial straight line which has to go through the origin of the stress–strain axis. This procedure also partly compensates for zero point errors encountered in experimental work of this nature.

On the basis of the above procedure, the mechanical properties of the different steels were determined and are given in Table 1. These mechanical properties were used in Equations 1 and 2 to produce the analytical stress–strain curves shown in Figures 2 to 4. The four distinctive stress–strain curves for longitudinal tension, LT, transverse tension, TT, longitudinal compression, LC, and transverse compression, TC, for the different stainless steels are shown in these curves.

WEIGHTED AVERAGE MECHANICAL PROPERTIES FOR A MEMBER SECTION

The weighted average mechanical properties are computed from the mechanical properties of strips which have been cut from the section. It can be considered that these strips are free of residual stresses caused by the cold forming process.

PREPARATION OF MEMBERS

The profiles chosen for this study were limited to lipped channel sections. The profiles were formed by a press braking process. The cross section of the lipped channels for the three different types of stainless steels is shown in Figure 5 and the dimensions are given in Table 2.

PREPARATION OF SPECIMENS

Tension and compression test specimens were prepared from each of the stainless steel sections. The member section was divided into a number of strips to study the effect of cold–forming on the corners and the flat portions, as shown in Figure 6. The length of the tension test specimens were 180 mm for the flat specimens between the corner specimens, and 320 mm for the corner specimens. The tension test specimens for the corners were taken longer to minimize the effect that the grips could have on the middle portion. The grips tend to crush the ends of the specimens. The nominal lengths of the compression test specimens were chosen as 70 mm to fit in a specially manufactured compression test fixture.

The width of the test specimens varied depending on where they were cut from the profile. The corner specimens were cut at the point where the corner started. The cross sectional area of the corner specimens were determined by first determining the mass. With the mass per unit volume of the steel known, the cross sectional area of the corner specimen could be determined and subsequently the stress in a stress–strain curve.

TESTING PROCEDURE

The same procedure and methods described previously were used to determine the mechanical properties. For the flat specimens, two strain gauges, one on either side of the specimen were used and for the corner specimens, one strain gauge on the outside of the specimen was used. Karren[11] used a similar procedure.

RESULTS

The mechanical properties, calculated from experimental stress–strain curves, obtained from tensile and compression tests done on the test specimens cut into strips from the profiles, for stainless steels Type 304, 316 and Type 3CR12 corrosion resisting steel are given in Tables 3 to 5. Also shown in these tables are the weighted average mechanical properties of the member section. By cutting the section into strips the section is released of all its residual stresses due to the cold forming process. Figures 7 to 9 represent the variation of the mechanical properties in the section

STUB COLUMN MECHANICAL PROPERTIES

Stub column tests were carried out to determine the mechanical properties of the full section. When a section is manufactured by a cold forming process, residual stresses are induced in the section. The results of the stub column tests will give the mechanical properties of a section which will include the effects of the residual stresses in the section as well as the effect of workhardening. The mechanical properties of the stub column tests are given in Tables 3 to 5.

COMPARISON OF STRESS–STRAIN CURVES

Figures 10 to 12 show stress–strain curves drawn with the mechanical properties obtained from experimental results. The three stress–strain curves were drawn by using Equations 1 and 2 and are:

1. The stress–strain curve of the virgin sheet drawn with the mechanical properties in Table 1 for longitudinal compression.

2. The stress–strain curve drawn by using the weighted average mechanical properties for longitudinal compression in Tables 3 to 5.

3. The stress–strain curve drawn by using the stub column mechanical properties in Tables 3 to 5.

DISCUSSION OF RESULTS

From Figures 10 to 12 it can be concluded that residual stresses influence the behaviour of stainless steel structural members. From these curves it can be seen that the virgin sheet mechanical properties give the lowest stress–strain curves and that the stress–strain curves drawn by using the weighted average mechanical properties give the highest stress–strain curves. It can be assumed that the latter mentioned stress—strain curves take into account the increase in strength in the corners due to cold work of forming. These stress–strain curves are free from residual stresses. The stress—strain curves drawn by using the stub column mechanical properties give the actual strength of the section and they take into account the increase in strength in the corners due to cold work of forming and also reflect the effect of residual stresses on the strength of a section.

It can be concluded that the difference in strength between the weighted average stress–strain curve and the stub column stress–strain curve is due to residual stresses in the section caused by cold–forming. These residual stresses decrease the strength of the section.

Residual stresses in sharp yielding carbon steels have been studied by Galambos.[2] The quantification of residual stresses in sharp yielding steels is relatively simple. However stainless steels have gradual yielding stress–strain curves. It is difficult to quantify the effects of measured residual stresses in the aforementioned stress–strain curves. Similar results were obtained by Van den Berg[9] in a study on hat sections.

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TABLE 1. MECHANICAL PROPERTIES OF STAINLESS STEEL

	SENSE AND DIRECTION OF STRESS			
MECHANICAL PROPERTY	LT	TT	LC	TC
Initial Elastic Modulus E(GPa)				
304	186,5	201,0	208,3	207,2
316	180,6	203,9	196,3	215,5
3CR12	196,7	227,6	201,1	228,2
Yield strength F_y(MPa)				
304	295,8	305,9	308,2	311,5
316	276,9	287,9	268,6	303,1
3CR12	299,4	341,2	309,4	347,7
Proportional limit F_p(MPa)				
304	184,2	223,3	168,0	225,6
316	179,1	198,2	154,7	229,5
3CR12	207,9	253,5	206,8	290,1
Ultimate Strength F_u(MPa)				
304	685	674		
316	621	619		
3CR12	462	500		
Ratio of F_p/F_y				
304	0,62	0,73	0,55	0,73
316	0,65	0,69	0,58	0,76
3CR12	0,70	0,74	0,67	0,80
Ratio of F_u/F_y				
304	2,32	2,21		
316	2,24	2,15		
3CR12	1,55	1,47		
Elongation (%)				
304	54,7	57,0		
316	56,2	60,5		
3CR12	32,3	28,1		

TABLE 2. DIMENSIONS OF LIPPED CHANNEL SECTIONS

	TYPE OF STEEL		
Dimension	304	316	3CR12
A(mm)	84,6	82,3	82,7
B(mm)	51,8	52,4	51,9
C(mm)	16,9	16,8	16,2
t(mm)	2,47	2,43	2,48
A(mm^2)	502,9	492,4	479,1

TABLE 3. THE EFFECT OF COLD–FORMING ON THE MECHANICAL PROPERTIES OF STAINLESS STEEL TYPE 304

	LONGITUDINAL TENSION								LONGITUDINAL COMPRESSION				
Specimen Number	Area mm^2	E_o GPa	F_y MPa	F_p MPa	F_u MPa	F_p F_y	F_u F_y	Elong %	Area mm^2	E_o GPa	F_y MPa	F_p MPa	F_p F_y
Virgin sheet	–	186,5	295,8	184,2	684,6	0,62	2,31	54,7	–	208,3	308,2	168,0	0,55
1	25,1	182,0	309,8	203,4	686	0,66	2,21	70,9	24,5	207,1	301,5	155,8	0,52
*2	17,1	226,1	520,1	249,6	811	0,48	1,60	36,0	19,0	228,1	551,0	171,4	0,31
3	25,7	190,7	307,9	190,7	699	0,62	2,27	55,7	24,5	208,2	291,4	153,6	0,53
4	24,4	186,6	289,4	185,5	689	0,64	2,38	60,9	24,3	205,8	284,2	153,3	0,54
5	24,8	187,3	295,6	187,5	686	0,63	2,32	50,0	24,2	206,5	297,1	155,0	0,52
*6	26,3	185,8	463,6	235,7	793	0,51	1,71	47,2	26,7	218,7	494,8	192,0	0,39
7	25,0	194,1	297,4	192,2	694	0,65	2,33	55,2	27,3	202,2	290,0	154,0	0,53
8	27,4	193,5	294,2	186,9	688	0,64	2,34	54,6	21,3	207,4	281,3	153,9	0,55
9	29,8	193,0	290,6	183,4	679	0,63	2,34	56,0	27,3	205,9	280,5	147,0	0,52
10	24,9	191,2	288,4	188,7	677	0,65	2,35	54,0	27,2	204,7	276,8	147,0	0,53
11	25,6	189,0	294,8	189,5	677	0,64	2,30	56,1	24,3	215,8	293,4	151,7	0,52
*12	26,2	204,5	470,6	249,7	795	0,53	1,69	36,1	26,7	179,5	489,6	255,3	0,52
13	24,5	195,4	294,9	185,5	676	0,63	2,29	53,3	24,1	205,9	294,0	155,8	0,53
14	25,6	189,1	284,6	189,3	670	0,67	2,35	57,0	24,1	193,7	268,4	140,1	0,52
15	25,5	192,8	299,3	197,5	678	0,66	2,27	56,4	24,1	201,8	289,1	152,1	0,53
*16	15,8	164,6	551,5	317,9	836	0,58	1,52	27,2	17,6	206,2	558,7	236,6	0,42
17	22,8	193,2	307,6	191,2	681	0,62	2,21	55,8	24,0	202,3	299,2	159,5	0,53
Weighted Average	–	191,7	336,4	203,4	708	0,61	2,10	52,8	401,2	205,7	338,4	165,9	0,55
Stub Column	–	–	–	–	–	–	–	–	–	197,3	338,0	172,3	0,51

* Corner Specimen

TABLE 4. THE EFFECT OF COLD–FORMING ON THE MECHANICAL PROPERTIES OF STAINLESS STEEL TYPE 316

	LONGITUDINAL TENSION								LONGITUDINAL COMPRESSION				
Specimen Number	Area mm^2	E_o GPa	F_y MPa	F_p MPa	F_u MPa	$\frac{F_p}{F_y}$	$\frac{F_u}{F_y}$	Elong %	Area mm^2	E_o GPa	F_y MPa	F_p MPa	$\frac{F_p}{F_y}$
Virgin sheet	–	180,6	276,9	179,1	620,8	0,64	2,24	56,1	–	196,3	268,6	154,7	0,57
1	20,9	189,1	295,7	188,5	611	0,64	2,07	45,2	20,8	191,7	297,3	205,3	0,69
*2	17,8	249,8	486,3	222,6	700	0,46	1,44	18,0	19,2	208,9	498,5	205,1	0,41
3	24,5	184,3	287,4	194,2	622	0,68	2,16	60,2	24,6	196,2	282,7	154,1	0,55
4	25,6	180,4	279,3	190,9	608	0,68	2,18	59,8	25,5	191,1	271,7	153,7	0,57
5	25,0	184,4	294,9	196,0	631	0,67	2,14	59,4	25,5	194,4	276,0	151,6	0,55
*6	23,6	192,1	444,9	240,7	676	0,54	1,52	46,3	25,5	198,1	463,9	221,2	0,48
7	25,5	184,5	290,3	189,9	630	0,65	2,17	64,7	24,8	193,6	274,9	151,6	0,55
8	24,5	183,5	285,3	188,7	623	0,66	2,18	56,8	26,2	190,2	270,8	157,9	0,58
9	32,5	181,4	283,2	191,8	629	0,68	2,22	65,4	29,5	194,0	271,4	150,8	0,56
10	25,3	184,3	286,2	192,9	626	0,67	2,19	66,0	29,5	199,3	272,6	152,4	0,56
11	24,6	183,5	286,4	192,3	614	0,67	2,14	58,0	25,7	194,1	275,1	154,3	0,56
*12	24,4	192,8	444,2	237,1	685	0,53	1,54	15,2	24,3	236,7	458,7	210,2	0,47
13	25,1	182,2	287,6	193,0	609	0,67	2,12	56,1	25,4	194,1	282,6	152,0	0,54
14	25,3	181,3	280,9	189,4	609	0,67	2,17	57,4	25,4	196,2	279,2	162,6	0,58
15	25,2	182,3	284,2	191,3	611	0,67	2,15	56,2	24,7	192,8	279,3	154,9	0,56
*16	17,3	297,6	486,9	221,0	710	0,45	1,46	22,2	18,5	198,1	463,9	221,2	0,48
17	21,7	183,6	289,5	193,1	610	0,67	2,11	59,1	24,5	196,3	295,1	158,0	0,54
Weighted Average	–	192,1	322,4	199,8	633	0,62	0,00	52,4	–	197,8	318,6	169,5	0,53
Stub Column	–	–	–	–	–	–	–	–	–	180,7	291,8	164,9	0,75

* Corner Specimen

TABLE 5. THE EFFECT OF COLD–FORMING ON THE MECHANICAL PROPERTIES OF STAINLESS STEEL TYPE 3CR12 CORROSION RESISTING STEEL

	LONGITUDINAL TENSION								LONGITUDINAL COMPRESSION				
Specimen Number	Area mm²	E_o GPa	F_y MPa	F_p MPa	F_u MPa	$\frac{F_p}{F_y}$	$\frac{F_u}{F_y}$	Elong %	Area mm²	E_o GPa	F_y MPa	F_p MPa	$\frac{F_p}{F_y}$
Virgin sheet	–	196,7	299,4	207,9	462	0,69	1,54	32,3	–	201,1	309,4	206,8	0,66
1	25,5	193,1	297,3	213,0	443	0,72	1,49	25,0	24,3	209,0	321,3	220,6	0,69
*2	17,9	217,6	518,6	281,1	532	0,54	1,03	14,8	21,0	209,4	501,8	250,0	0,50
3	25,0	194,4	299,4	214,3	450	0,72	1,50	33,7	25,1	210,9	307,2	200,6	0,65
4	25,4	197,0	297,3	217,6	448	0,73	1,51	31,7	25,0	204,5	312,6	207,6	0,66
5	22,9	192,5	292,2	213,0	442	0,73	1,51	33,4	24,5	209,3	309,0	183,7	0,59
*6	26,1	210,8	485,8	279,4	525	0,58	1,08	14,8	24,8	200,2	509,3	339,7	0,67
7	25,7	194,9	291,9	215,4	443	0,74	1,52	33,4	26,2	206,1	309,2	206,4	0,67
8	24,9	194,2	293,0	210,0	444	0,72	1,52	20,8	26,2	205,8	308,8	205,3	0,67
9	25,4	194,7	293,2	216,4	447	0,74	1,53	23,5	26,4	207,1	310,8	205,4	0,66
10	24,3	195,0	292,2	216,4	441	0,74	1,51	18,5	26,1	217,4	312,4	204,5	0,66
11	24,6	193,1	289,7	212,7	444	0,73	1,53	22,3	26,0	216,0	308,9	209,4	0,68
*12	26,6	203,7	481,8	278,7	523	0,58	1,09	14,8	27,6	209,4	501,8	250,0	0,50
13	22,9	196,8	290,5	207,4	444	0,71	1,53	31,8	24,4	210,0	306,9	191,1	0,62
14	22,8	192,0	283,8	208,2	438	0,73	1,54	34,6	24,6	205,8	308,5	204,2	0,66
15	24,5	192,8	285,5	208,8	439	0,73	1,54	18,9	25,1	217,7	315,2	188,8	0,60
*16	18,2	218,1	528,2	304,1	541	0,58	1,02	14,8	17,8	196,9	535,5	348,5	0,65
17	23,9	195,4	293,8	203,8	446	0,69	1,52	31,3	24,3	208,1	324,3	212,5	0,66
Weighted Average	–	197,8	337,7	228,0	463	0,68	1,37	24,8	–	208,7	355,1	222,8	0,63
Stub Column	–	–	–	–	–	–	–	–	–	195,9	331,3	213,4	0,64

* Corner Specimen

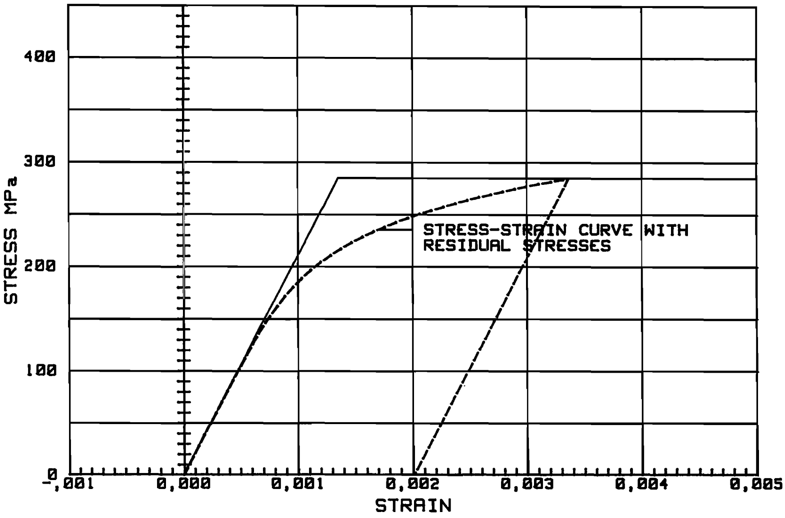

FIGURE 1 TYPICAL STRESS-STRAIN CURVES FOR CARBON STEELS

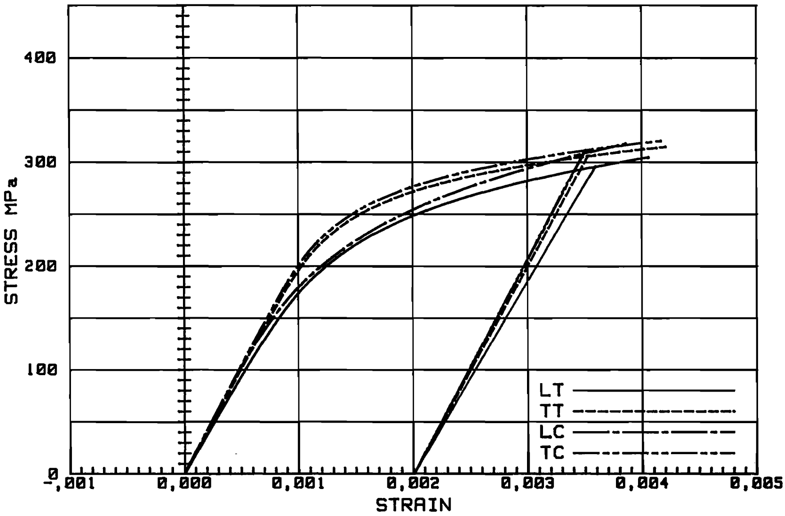

FIGURE 2 ANALYTICAL STRESS-STRAIN CURVES FOR STAINLESS STEEL TYPE 304

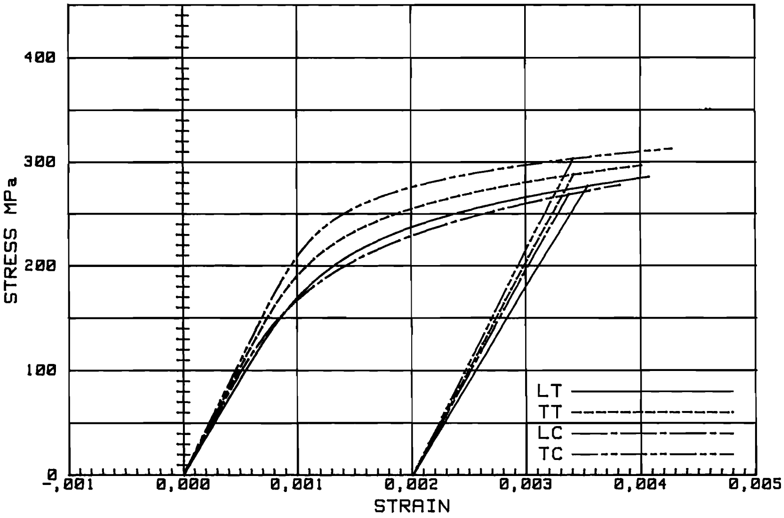

FIGURE 3 ANALYTICAL STRESS-STRAIN CURVES FOR STAINLESS STEEL TYPE 316

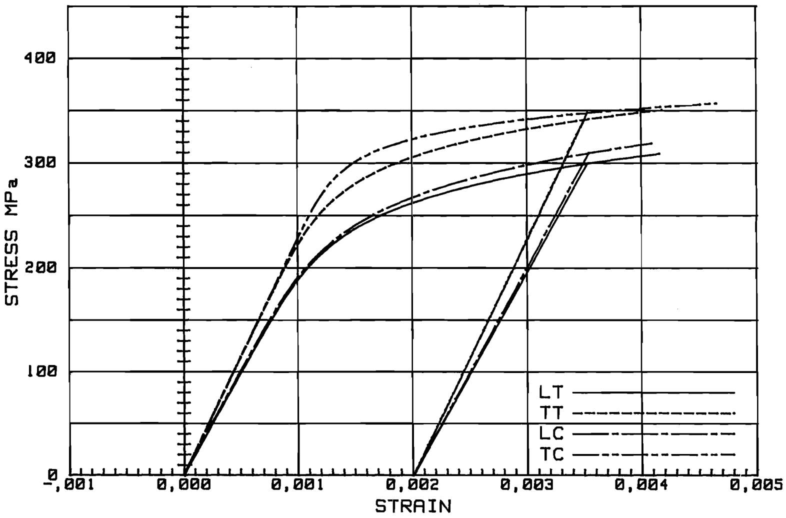

FIGURE 4 ANALYTICAL STRESS-STRAIN CURVES FOR TYPE 3CR12 CORROSION RESISTING STEEL

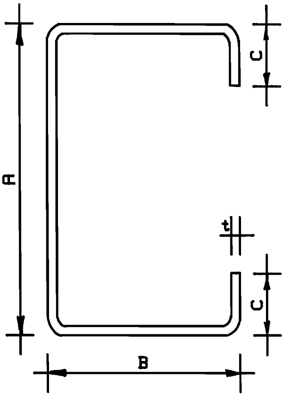

FIGURE 5 DIMENSIONS OF CHANNEL SECTION

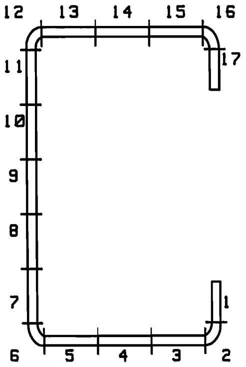

FIGURE 6 SECTIONING OF CHANNEL SECTION

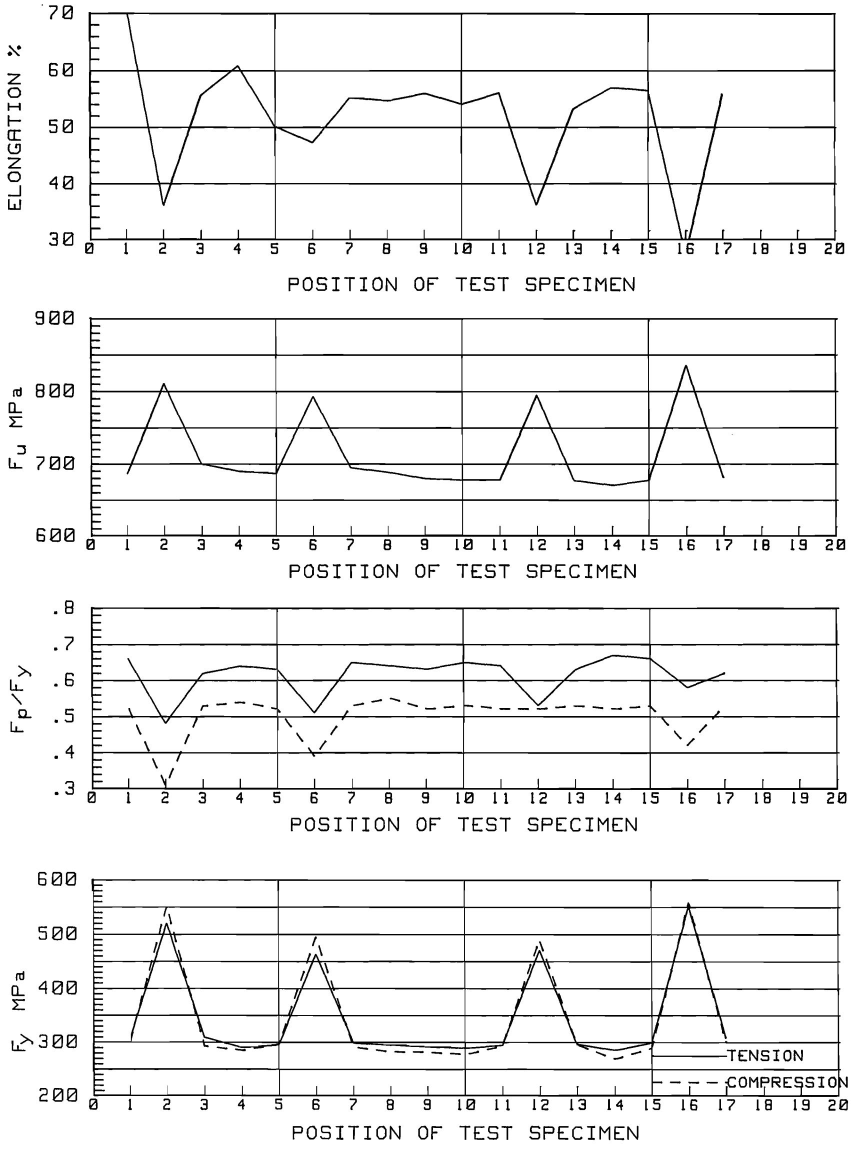

FIGURE 7 VARIATION OF MECHANICAL PROPERTIES FOR STAINLESS STEEL TYPE 304

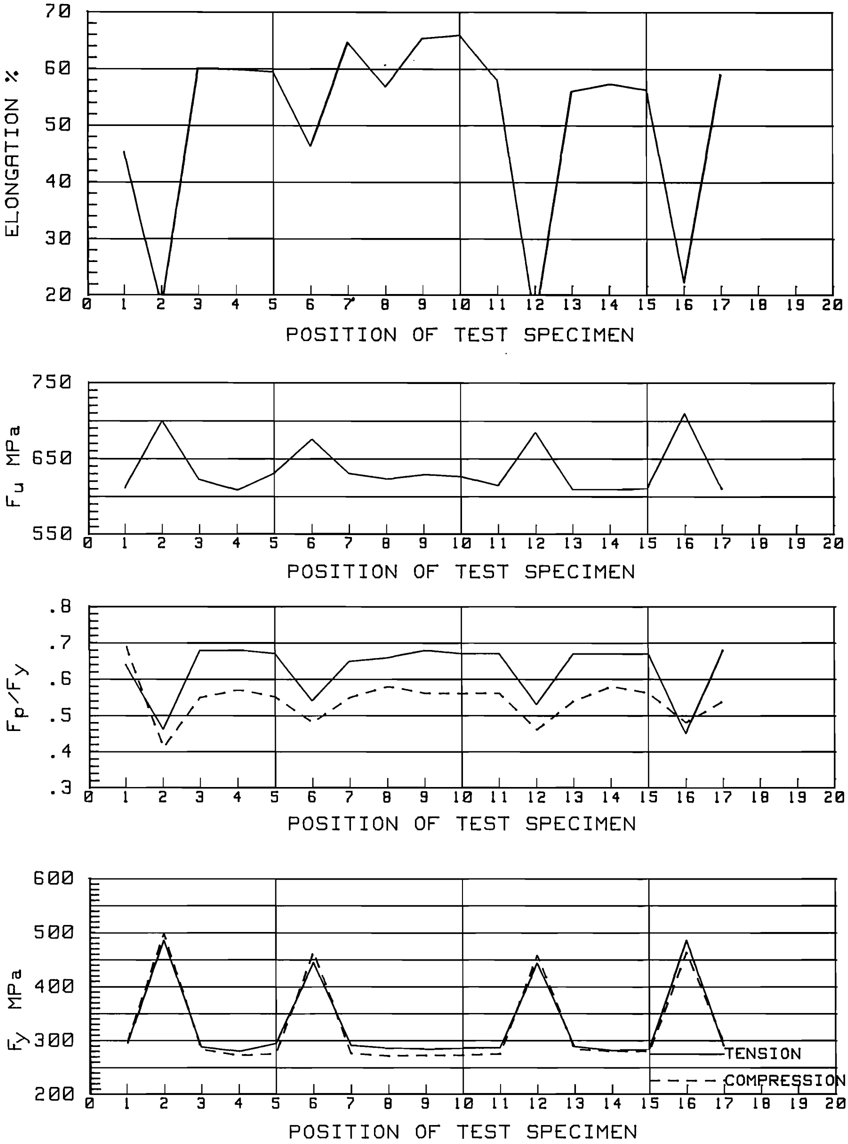

FIGURE 8 VARIATION OF MECHANICAL PROPERTIES FOR STAINLESS STEEL TYPE 316

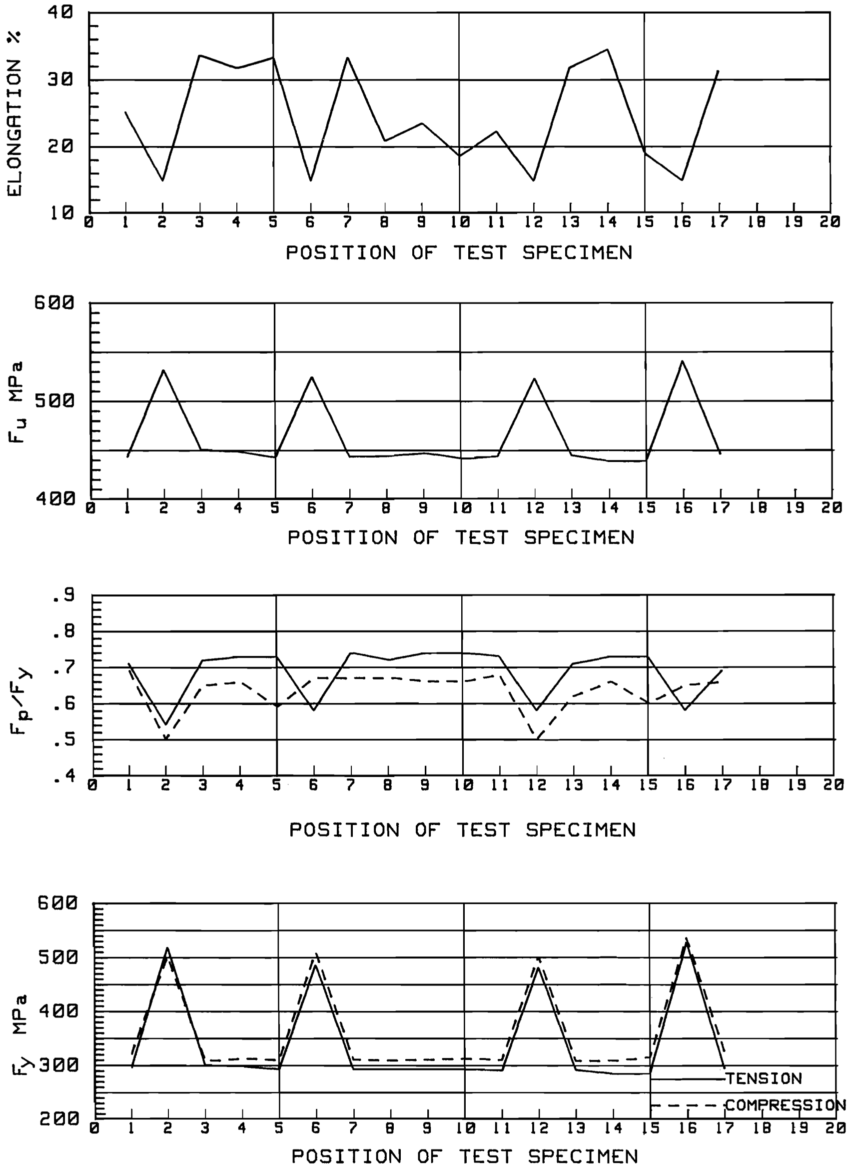

FIGURE 9 VARIATION OF MECHANICAL PROPERTIES FOR TYPE 3CR12 CORROSION RESISTING STEEL

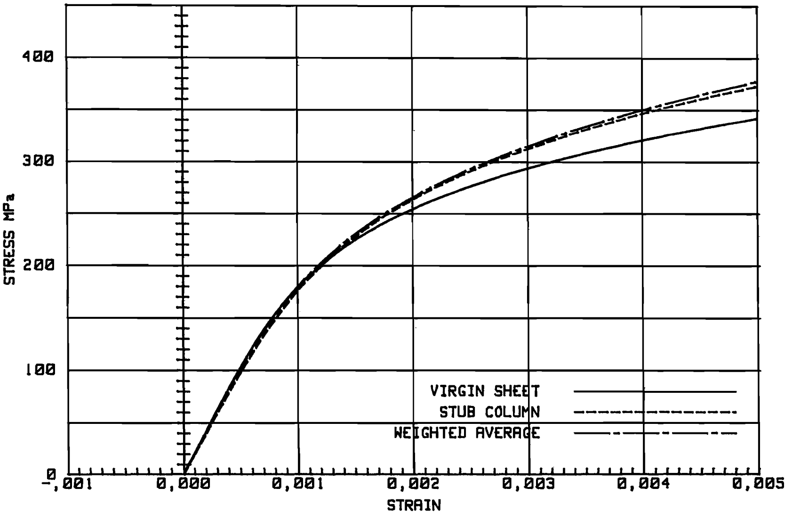

FIGURE 10 COMPARISON OF VARIOUS STRESS-STRAIN CURVES FOR STAINLESS STEEL TYPE 304

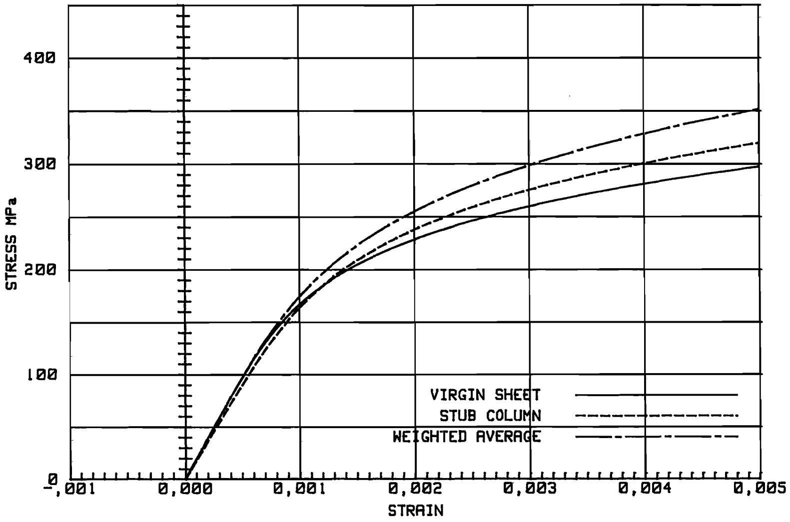

FIGURE 11 COMPARISON OF VARIOUS STRESS-STRAIN CURVES FOR STAINLESS STEEL TYPE 316

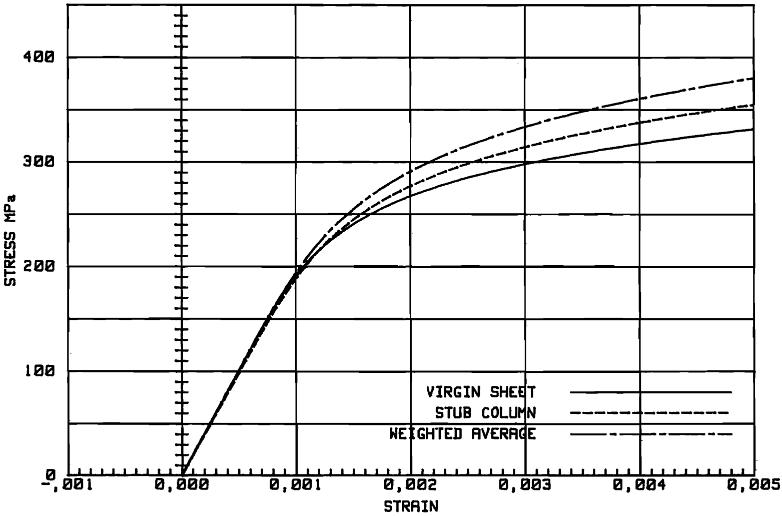

FIGURE 12 COMPARISON OF VARIOUS STRESS-STRAIN CURVES FOR
TYPE 3CR12 CORROSION RESISTING STEEL